

## **REMARKS**

In view of the following remarks, reconsideration of the rejections and further examination are respectfully requested.

The specification and abstract have been reviewed and revised to improve their English grammar. The amendments to the specification and abstract have been incorporated into a substitute specification and abstract. Attached are two versions of the substitute specification, a marked-up version showing the revisions, as well as a clean version. No new matter has been added.

Claims 1, 2, 4, 6, 8, and 10-12 have been amended to make a number of editorial revisions thereto. These editorial revisions have been made to place the claims in better U.S. form. Further, these editorial revisions have not been made to narrow the scope of protection of the claims, or to address issues related to patentability, and therefore, these amendments should not be construed as limiting the scope of equivalents of the claimed features offered by the Doctrine of Equivalents.

Claims 1, 8, 9, and 12 were rejected under 35 U.S.C. § 102(b) as being anticipated by Weber (U.S. 5,864,261). Further, claims 2-7, 10, and 11 were rejected under 35 U.S.C. § 103(a) as being unpatentable over Weber. In addition, claims 1-12 were rejected under 35 U.S.C. § 103(a) as being unpatentable over Ella et al. (U.S. 6,518,860) in view of Tikka et al. (U.S. 6,407,649). These rejections are respectfully traversed for the following reasons.

Each of independent claims 1 and 10-12 includes recitations directed to an acoustic resonator. According to claims 1 and 10-12 the acoustic resonator includes an acoustic mirror layer and a piezoelectric thin film vibrator disposed on the acoustic mirror layer. Further, claims 1 and 10-12 recite that the piezoelectric thin film vibrator includes a lower electrode, a piezoelectric thin film, and an upper electrode. Moreover, claims 1 and 10-12 recite that a sum of a thickness of the lower electrode and a thickness of upper electrode is between 5% and 60% of a thickness of the entire piezoelectric thin film vibrator, wherein the thickness of the lower electrode is larger than the thickness of the upper electrode. The Weber, Ella, and Tikka references, or any combination thereof, do not disclose or suggest the above-mentioned features of claims 1 and 10-12.

Rather, Weber teaches a thin film resonator 30 having an upper electrode 36, a piezoelectric layer 35, and a bottom electrode 37, wherein the thin film resonator 30 is disposed on an acoustical isolator 40 comprised of stack pairs 42, 43, 44, and 45, and wherein the uppermost constituent of the stack pair 42 is actually the bottom electrode 37 (see Fig. 1; col. 4, lines 35-36; col. 4, lines 57-58).

Thus, in view of the above, it is clear that Weber teaches that the thin film resonator and the acoustical isolator share the bottom electrode, but does not disclose or suggest the piezoelectric thin film vibrator disposed on the acoustical mirror layer such that the bottom electrode of the piezoelectric film layer is not a part of the acoustical mirror, as required by claims 1 and 10-12. In other words, Weber teaches that the bottom electrode is part of the resonator and part of the acoustical isolator, but does not disclose or suggest that the bottom electrode is just an element of the piezoelectric thin film vibrator. Therefore, in view of the above, it is clear that Weber does not anticipate claims 1 and 10-12.

Further, Weber merely describes an example of a resonator, but does not disclose or suggest the effect of the invention of claims 1 and 10-12, such that the acoustic resonator has a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode (see page 51, lines 11-14 of the present application). Accordingly, Weber does not disclose or suggest the structure or the result of the structure defined by claims 1 and 10-12. Therefore, because of the above-mentioned distinctions it is believed clear that claims 1 and 10-12 are not anticipated by Weber.

In view of the above, it is respectfully submitted that Weber does not suggest the above-discussed limitations of claims 1 and 10-12. Therefore, it would not have been obvious to one of ordinary skill in the art to modify Weber so as to obtain the invention of claims 1 and 10-12. Accordingly, it is respectfully submitted that independent claims 1 and 10-12 and dependent claims 2-9 are clearly allowable over Weber.

In addition, the 35 U.S.C. §103(a) rejection of claims 1-12, for being unpatentable over the combination of Ella and Tikka, is respectfully traversed for the following reasons.

This rejection cites the Tikka reference for teaching that the bottom electrode of the piezoelectric thin film vibrator is thicker than the top electrode, as recited in claims 1 and 10-12. Specifically, the rejection states that in view of the Tx tuning layer and the bottom electrode of Fig. 7 it would be obvious to have a bottom electrode that is thicker than the top electrode. However, it is clear that Tikka teaches a resonator including separate and distinct layers including a top electrode, a piezoelectric layer, a Tx tuning layer, and a bottom electrode, wherein the Tx tuning layer is not the bottom electrode (see Fig. 7).

Thus, in view of the above, it is clear that Tikka discloses a resonator including 4 separate and distinct layers (i.e., top and bottom electrodes, piezoelectric layer, and Tx tuning layer), but does not disclose or suggest that the bottom electrode is thicker than the top electrode, as required by claims 1 and 10-12. In other words, two separate and distinct layers (i.e. bottom electrode and a Tx tuning layer) cannot be combined and compared to a single bottom electrode. Further, it is noted that there can only be one bottom electrode layer and any layer above the bottom layer (i.e., Tx tuning layer) is not a bottom layer and, thus, cannot be called a bottom electrode layer. Therefore, it is clear that the Tikka reference does not disclose or suggest the above-mentioned feature of claims 1 and 10-12 and therefore it is clear that the combination of Ella and Tikka does not render claims 1 and 10-12 obvious.

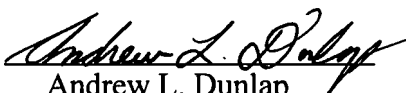
It is also noted that the effect of the invention of claims 1 and 10-12, as discussed above, also, is not disclosed or suggested by the Ella and Tikka references.

In view of the above, it is respectfully submitted that Ella and Tikka do not anticipate the invention as recited in independent claims 1 and 10-12. Therefore, it would not have been obvious to one of ordinary skill in the art to modify Ella and Tikka so as to obtain the invention of independent claims 1 and 10-12. Accordingly, it is respectfully submitted that independent claims 1 and 10-12 and dependent claims 2-9 are clearly allowable over the combination of Ella and Tikka.

In view of the above amendments and remarks, it is submitted that the present application is now in condition for allowance and an early notification thereof is earnestly requested. The Examiner is invited to contact the undersigned by telephone to resolve any remaining issues.

Respectfully submitted,

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DESCRIPTION

ACOUSTIC MIRROR TYPE THIN FILM BULK ACOUSTIC RESONATOR, AND FILTER,  
DUPLEXER AND COMMUNICATION APPARATUS COMPRISING THE SAME

5

TECHNICAL FIELD BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a resonator for use in a high frequency circuit of a wireless apparatus or the like. More particularly, the present invention relates to a thin film bulk acoustic resonator having an acoustic mirror structure, and a filter, a duplexer and a communication apparatus which each comprise the same.

15 2. Description of the Related Art ~~BACKGROUND ART~~

With the recent advances in downsizing and cost cutting of wireless communication ~~apparatuses~~ devices, there is an increasing demand for miniaturization and integration of a filter mounted thereon. To meet the demand, a dielectric filter, a multilayer filter, a bulk acoustic filter and the like have been developed. The bulk acoustic filter includes a thin film bulk acoustic resonator which utilizes a piezoelectric thin film.

The thin film bulk acoustic resonator has a structure such that a piezoelectric thin film is interposed between two electrodes. When a voltage is applied between the electrodes of the thin film

bulk acoustic resonator, a piezoelectric effect which is induced in response to the voltage application causes mechanical piezoelectric vibration (elastic vibration).

The thin film bulk acoustic resonator includes an acoustic mirror type thin film bulk acoustic resonator with a mirror structure which utilizes an acoustic mirror effect. FIG. 28 is a cross-sectional view of a conventional acoustic mirror type thin film bulk acoustic resonator. In FIG. 28, an acoustic mirror type thin film bulk acoustic resonator 907a comprises a substrate 901a, acoustic mirror layers 902a and 903a, a lower electrode 904a, a piezoelectric thin film 905a, and an upper electrode 906a.

The acoustic mirror layers 902a and 903a are formed on the substrate 901a. The acoustic mirror layers 902a and 903a are composed of a combination of a plurality of materials having different acoustic impedances. A piezoelectric thin film vibrator 909a, which is composed of the lower electrode 904a, the upper electrode 906a and the piezoelectric thin film 905a interposed therebetween. The piezoelectric thin film vibrator 909a is provided on the acoustic mirror layers 902a and 903a.

In a general acoustic mirror layer, high acoustic impedance materials (the acoustic mirror layers 902a) and low acoustic impedance materials (the acoustic mirror layers 903a) are alternately disposed so that an impedance mismatch surface is formed on an interface between each layer. Each acoustic mirror layer has a thickness which is equal to one fourth of an acoustic

wavelength calculated from a resonant frequency in free space of the piezoelectric thin film vibrator 909a. The size of one fourth of the acoustic wavelength is calculated by:

5  $\lambda \text{ (wavelength)}/4 = v/(4 \cdot f_r) \text{ or } v/(4 \cdot f_a)$

where  $v$  represents the speed of sound transmitting through each of the acoustic mirror layers 902a and 903a,  $f_r$  represents the resonant frequency of the piezoelectric thin film vibrator 909a, 10 and  $f_a$  represents the antiresonant frequency of the piezoelectric thin film vibrator 909a.

Thus, a vibration wave (sonic wave) induced in the piezoelectric thin film vibrator 909a is transmitted through each acoustic mirror layer and is reflected from the interface 15 (impedance mismatch surface) of each layer. The reflected vibration waves are combined at a resonant frequency (antiresonant frequency) and in the same phase, thereby improving resonance characteristics. The resonance bandwidth of the resonance characteristics can be increased by increasing an impedance mismatch ratio, i.e., an impedance ratio of the high impedance 20 layer to the low impedance layer. The acoustic impedance of the substrate with respect to the piezoelectric thin film vibrator can be reduced by increasing the number of acoustic mirror layers, thereby improving the resonance characteristics. This has been 25 well known. However, conventionally, a thickness ( $C$ ) of the lower

electrode 904a is not strictly defined.

Conventional techniques are disclosed in, for example:

Patent Publication 1: Japanese Patent Laid-Open  
Publication No. 9-199978;

5 Patent Publication 2: Japanese Patent Laid-Open  
Publication No. 6-295181; and

Patent Publication 3: Japanese Patent Laid-Open  
Publication No. 2002-41052.

FIG. 29 is a diagram showing a vibration distribution in  
10 the acoustic mirror type thin film bulk acoustic resonator 907a  
of FIG. 28. When the thicknesses of the upper electrode 906a and  
the lower electrode 904a are considerably small compared to the  
thickness of the piezoelectric thin film 905a, an acoustic  
wavelength is  $\lambda/2$  in the piezoelectric thin film vibrator 909a  
15 as in FIG. 29. In this case, by setting the thickness of each  
mirror layer to be one fourth of an acoustic wavelength at the  
resonant frequency (or antiresonant frequency) of the  
piezoelectric thin film vibrator, reflected vibration waves are  
combined in the same phase, thereby making it possible to improve  
20 resonance characteristics.

However, in actual devices, the thickness of the electrode  
is often significant with respect to the thickness of the  
piezoelectric thin film. Therefore, the vibration distribution  
in the piezoelectric thin film vibrator deviates from  $\lambda/2$ .  
25 Therefore, when the thickness of each mirror layer is simply set



tobe one fourth of the acoustic wavelength at the resonant frequency  
(or the antiresonant frequency), reflection does not take place  
exactly at  $\lambda/4$ . As a result, the frequency of reflected vibration  
is shifted, so that resonance characteristics, particularly the  
5 bandwidth of resonance ( $\Delta f$ ), is deteriorated.

#### DISCLOSURE SUMMARY OF THE INVENTION

Therefore, an object of the present invention is to provide  
an acoustic mirror type thin film bulk acoustic resonator having  
10 excellent resonance characteristics.

To achieve the object, the present invention has the  
following features. The present invention provides an acoustic  
mirror type thin film bulk acoustic resonator comprising a  
substrate, and an acoustic mirror layer provided on the substrate,  
15 including a plurality of impedance layers alternately having a  
high acoustic impedance and a low acoustic impedance. The acoustic  
resonator further includes, and a piezoelectric thin film vibrator  
provided on the acoustic mirror layer,-- The piezoelectric thin  
film vibrator including a lower electrode, a piezoelectric thin  
20 film and an upper electrode. The sum of a thickness of the lower  
electrode and a thickness of the upper electrode is between 5%  
~~or more and 60% or less of a whole thickness of the piezoelectric~~  
thin film vibrator, and the thickness of the lower electrode is  
larger than the thickness of the upper electrode.

25 According to the present invention, the thickness of the

lower electrode is larger than the thickness of the upper electrode, and therefore, a resonance bandwidth can be broadened as compared to when the thickness of the lower electrode is equal to the thickness of the upper electrode. By broadening the resonance bandwidth,  
5 it is possible to prevent a deterioration in resonance characteristics due to variations in the thickness.

Preferably, the plurality of impedance layers may include a plurality of low acoustic impedance layers and a plurality of high acoustic impedance layers which are alternately disposed,  
10 ~~and wherein~~ an uppermost one of the low acoustic impedance layers which contacts the lower electrode, may have a thickness of one fourth of an acoustic wavelength defined from a resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be further broadened.

15 Preferably, each of the plurality of low acoustic impedance layers may have a thickness of one fourth of the acoustic wavelength defined from the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be further broadened.

20 Preferably, the plurality of impedance layers may include a plurality of low acoustic impedance layers and a plurality of high acoustic impedance layers which are alternately disposed, ~~and wherein~~ an uppermost one of the low acoustic impedance layers which contacts the lower electrode, may have a thickness of less  
25 than one fourth of an acoustic wavelength defined from a resonant

frequency in free space of the piezoelectric thin film vibrator.  
Thereby, the resonance bandwidth can be further broadened.

Preferably, each of the plurality of low acoustic impedance  
layers may have a thickness of less than one fourth of the acoustic  
5 wavelength defined from the resonant frequency in free space of  
the piezoelectric thin film vibrator. Thereby, the resonance  
bandwidth can be further broadened.

Preferably, the plurality of impedance layers may include  
a plurality of low acoustic impedance layers and a plurality of  
10 high acoustic impedance layers which are alternately disposed,  
~~and wherein~~ an uppermost one of the low acoustic impedance layers  
which contacts the lower electrode<sub>7</sub> may have a thickness of more  
than one fourth of an acoustic wavelength defined from a resonant  
frequency in free space of the piezoelectric thin film vibrator.  
15 Thereby, the resonance bandwidth can be further broadened.

Preferably, each of the plurality of low acoustic impedance  
layers may have a thickness of more than one fourth of the acoustic  
wavelength defined from the resonant frequency in free space of  
the piezoelectric thin film vibrator. Thereby, the resonance  
20 bandwidth can be further broadened.

Preferably, the plurality of impedance layers may include  
a plurality of low acoustic impedance layers and a plurality of  
high acoustic impedance layers which are alternately disposed,  
~~and wherein~~ at least an uppermost one of the plurality of low acoustic  
25 impedance layer<sub>7</sub> may have a thickness different from one fourth

of an acoustic wavelength defined from a resonant frequency in free space of the piezoelectric thin film vibrator, and wherein an uppermost one of the high acoustic impedance layers may have a thickness different from one fourth of the acoustic wavelength defined from the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be further broadened.

Preferably, each of the plurality of high acoustic impedance layers may have a thickness different from one fourth of the acoustic wavelength defined from the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be further broadened.

The present invention also provides a filter comprising two or more thin film bulk acoustic resonators which are connected in a ladder form, wherein at least one of the thin film bulk acoustic resonators comprises a substrate, an acoustic mirror layer provided on the substrate, the acoustic mirror including a plurality of impedance layers alternately having a high acoustic impedance and a low acoustic impedance. Further, the at least one of the thin film bulk acoustic resonators includes ~~and~~ a piezoelectric thin film vibrator provided on the acoustic mirror layer, including a lower electrode, a piezoelectric thin film and an upper electrode, wherein the sum of a thickness of the lower electrode and a thickness of the upper electrode is between 5% or more and 60% or less of a ~~whole~~ thickness of the piezoelectric thin film vibrator, and

the thickness of the lower electrode is larger than the thickness of the upper electrode.

The present invention also provides a duplexer comprising a transmission filter and a reception filter, wherein at least one of the transmission filter and the reception filter comprises two or more thin film bulk acoustic resonators which are connected in a ladder form, and at least one of the thin film bulk acoustic resonators comprises a substrate, an acoustic mirror layer provided on the substrate, the acoustic mirror layer including a plurality of impedance layers alternately having a high acoustic impedance and a low acoustic impedance. Further, the at least one of the thin film bulk acoustic resonators includes ~~and~~ a piezoelectric thin film vibrator provided on the acoustic mirror layer, including a lower electrode, a piezoelectric thin film and an upper electrode, wherein the sum of a thickness of the lower electrode and a thickness of the upper electrode is between 5% or more and 60% or less of a ~~whole~~ thickness of the piezoelectric thin film vibrator, and the thickness of the lower electrode is larger than the thickness of the upper electrode.

The present invention also provides a communication apparatus comprising at least one thin film ~~one~~ bulk acoustic resonator, wherein the at least one thin film ~~one~~ bulk acoustic resonator comprises a substrate, an acoustic mirror layer provided on the substrate, the acoustic mirror layer including a plurality of impedance layers alternately having a high acoustic impedance

and a low acoustic impedance. Further, the at least one thin film  
bulk acoustic resonator includes~~and~~ a piezoelectric thin film  
vibrator provided on the acoustic mirror layer, the piezoelectric  
thin film vibrator including a lower electrode, a piezoelectric  
5 thin film and an upper electrode, wherein the sum of a thickness  
of the lower electrode and a thickness of the upper electrode is  
between 5% ~~or more~~ and 60% ~~or less~~ of a whole thickness of the  
piezoelectric thin film vibrator, and the thickness of the lower  
electrode is larger than the thickness of the upper electrode.

10 According to the present invention, by causing the thickness  
of the lower electrode to be larger than the thickness of the upper  
electrode, it is possible to provide an acoustic mirror type thin  
film piezoelectric resonator in which a resonance bandwidth can  
be broadened, and a filter, a duplexer and a communication apparatus  
15 comprising the same. Also, by broadening the resonance bandwidth,  
it is possible to provide an acoustic mirror type thin film  
piezoelectric resonator in which a deterioration in resonance  
characteristics due to variations in the thickness of the low  
acoustic impedance layer can be prevented, and a filter, a duplexer  
20 and a communication apparatus comprising the same.

These and other objects, features, aspects and advantages  
of the present invention will become more apparent from the  
following detailed description of the present invention when taken  
in conjunction with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a first embodiment of the present invention,

5        FIG. 2 is a graph showing a change in resonance band when a thickness of a low acoustic impedance layer 103b is changed while fixing the other values,

FIG. 3 is a diagram for explaining how a most preferable thickness of the low acoustic impedance layer 103b varies depending  
10 on conditions of a piezoelectric thin film vibrator 109b,

FIG. 4 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a second embodiment of the present invention,

FIG. 5 is a graph showing a change in resonance band when  
15 a thickness of a high acoustic impedance layer 202b is changed while fixing the other values,

FIG. 6 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a third embodiment of the present invention,

20        FIG. 7 is a graph showing a change in resonance band when a thickness of a high acoustic impedance layer 302b and a thickness of a low acoustic impedance layer 303b are simultaneously changed at the same rate,

FIG. 8 is a graph for explaining that an effect of the present  
25 invention is obtained to a further extent with an increase in

thicknesses of upper and lower electrodes,

FIG. 9 is a graph showing for explaining that the effect of the present invention is obtained to a further extent with an increase in the ratio of an acoustic impedance of a high acoustic impedance layer to an acoustic impedance of a low acoustic impedance layer,

FIG. 10 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a fourth embodiment of the present invention,

10 FIG. 11 is a graph showing a change in resonance band when a thickness of an uppermost low acoustic impedance layer 403b is changed while fixing the other values,

FIG. 12 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a fifth embodiment of the present invention,

FIG. 13 is a graph showing a band ratio where an electrode ratio is 10%,

FIG. 14 is a graph showing a band ratio where the electrode ratio is 14%,

20 FIG. 15 is a graph showing a band ratio where the electrode ratio is 20%,

FIG. 16 is a graph showing a band ratio where the electrode ratio is 30%,

FIG. 17 is a graph showing a band ratio where the electrode ratio is 40%,



FIG. 18 is a graph showing a band ratio where the electrode ratio is 50%,

FIG. 19 is a graph showing a band ratio where the electrode ratio is 60%,

5 FIG. 20 is a graph showing a band ratio where the electrode ratio is 70%,

FIG. 21 is a graph showing a band ratio where the electrode ratio is 80%,

FIG. 22 is a graph showing an optimum value of an upper/lower  
10 ratio,

FIG. 23 is a graph showing a band ratio when the electrode ratio is 5%,

FIGS. 24A and 24B are diagrams showing exemplary filters comprising acoustic mirror type thin film bulk acoustic resonators  
15 of the present invention,

FIG. 25 is a diagram showing a first exemplary apparatus comprising an acoustic mirror type thin film bulk acoustic resonator of the present invention,

FIG. 26 is a diagram showing a second exemplary apparatus  
20 comprising an acoustic mirror type thin film bulk acoustic resonator of the present invention,

FIG. 27 is a diagram showing a third exemplary apparatus comprising an acoustic resonator of the present invention,

FIG. 28 is a cross-sectional view of a conventional acoustic  
25 mirror type thin film bulk acoustic resonator, and

FIG. 29 is a diagram showing an ideal vibration distribution in an acoustic mirror type thin film bulk acoustic resonator 907a of FIG. 28.

5 ~~BEST MODE FOR CARRYING OUT~~ DETAILED DESCRIPTION OF THE INVENTION

Hereinafter, embodiments of the present invention will be described with reference to the accompanying drawings.

(First embodiment)

FIG. 1 is a cross-sectional view of an acoustic mirror type  
10 thin film bulk acoustic resonator according to a first embodiment of the present invention. In FIG. 1, the acoustic mirror type thin film bulk acoustic resonator 107b comprises a substrate 101b, high acoustic impedance layers 102b, low acoustic impedance layers 103b, a lower electrode 104b, a piezoelectric thin  
15 film 105b, and an upper electrode 106b.

The number of the high acoustic impedance layers 102b is two in FIG. 1, or alternatively, may be one, or three or more. Also, the number of the low acoustic impedance layers 103b is two in FIG. 1, or alternatively, may be one, or three or more. Note  
20 that an uppermost one of the low acoustic impedance layers 103b is formed immediately below the lower electrode 104b. The low acoustic impedance layers 103b and the high acoustic impedance layers 102b are alternately formed.

An acoustic mirror layer 108b, which is composed of the high  
25 acoustic impedance layers 102b and the low acoustic impedance

layers 103b, is provided on the substrate 101b. On the acoustic mirror layer 108b, a piezoelectric thin film vibrator 109b, which is composed of the lower electrode 104b, the piezoelectric thin film 105b and the upper electrode 106b, is provided.

5       The high acoustic impedance layer 102b is made of a high acoustic impedance material, such as tungsten (W), molybdenum (Mo) or the like. A thickness (B) of the high acoustic impedance layer 102b is equal to one fourth of an acoustic wavelength which is calculated from a resonant frequency (antiresonant frequency)  
10   in free space of the piezoelectric thin film vibrator 109b.

      The low acoustic impedance layer 103b is made of a low acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or the like. A thickness (A1) of the low acoustic impedance layer 103b is equal to a thickness which maximizes a bandwidth of resonance  
15   characteristics. The present inventors found that the thickness (A1) of the low acoustic impedance layer 103b which maximizes the bandwidth of the resonance characteristics is smaller than the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the  
20   piezoelectric thin film vibrator 109b.

      The lower electrode 104b is made of, for example, molybdenum (Mo), aluminum (Al), platinum (Pt), gold (Au) or the like.

      The piezoelectric thin film 105b is made of, for example, aluminum nitride (AlN), zinc oxide (ZnO), or the like.

25       The upper electrode 106b is made of, for example, molybdenum

(Mo), aluminum (Al), platinum (Pt), gold (Au), or the like.

In a production process of the acoustic mirror type thin film bulk acoustic resonator 107b, the thickness of each acoustic mirror layer varies in one chip due to an influence of surface roughness of the substrate 101b, the low acoustic impedance layer 103b and the high acoustic impedance layer 102b.

In addition, film forming conditions vary depending on a position on a wafer, resulting in variations in chip. Due to an influence of the chip variation, the thickness of each acoustic mirror layer varies among a plurality of chips.

The magnitude of the variation is about 1% at maximum with respect to the thickness.

Therefore, the thickness (Al) of the low acoustic impedance layer 103b is preferably lower by 1% or more than one fourth of the acoustic wavelength calculated from the resonant frequency in free space of the piezoelectric thin film vibrator 109b, taking its variations into consideration.

FIG. 2 is a graph showing a change in resonance band when the thickness of the low acoustic impedance layer 103b is changed while fixing the other values. Here, it is assumed that the lower electrode 104b is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ , the piezoelectric thin film 105b is made of aluminum nitride and has a thickness of 2.0  $\mu\text{m}$ , and the upper electrode 106b is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ .

In FIG. 2, the horizontal axis represents a value obtained

by standardizing the thickness of the low acoustic impedance layer 103b using the size of one fourth of the acoustic wavelength  $\lambda$  calculated from the resonant frequency in free space of the piezoelectric thin film vibrator 109b (hereinafter referred to as "ideal length  $\lambda/4$ "). The vertical axis represents a value obtained by standardizing a change in a resonance bandwidth using a bandwidth ( $\Delta f$ ) which is obtained when the thickness of the low acoustic impedance layer 103b is equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thickness of the low acoustic impedance layer 103b is equal to the ideal length  $\lambda/4$ .

As can be seen from FIG. 2, the thickness of the low acoustic impedance layer 103b which maximizes the resonance bandwidth is obtained at a thickness point Y which is smaller than a thickness point X corresponding to the ideal length  $\lambda/4$ . Therefore, the thickness of the low acoustic impedance layer 103b is preferably smaller than the size of one fourth of the acoustic wavelength which is calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

For example, the degree of a change in resonance bandwidth at the point X is compared with the degree of a change in resonance bandwidth at the point Y, assuming that there is, for example, a variation of  $\pm 1\%$  in thickness. In this case, it will be found that the change degree is smaller at the point Y than at the point X.

Therefore, when the thickness at the point Y is determined to be the thickness (A') of the low acoustic impedance layer 103b, a change in resonance band due to a variation in thickness can be further reduced. Thereby, an influence of the thickness variation  
5 can be minimized.

Also, as can be seen from FIG. 2, when the thickness of the low acoustic impedance layer 103b is more than 0.8 times the length  $\lambda/4$ , i.e., more than [the ideal length  $\lambda/4$  minus 20.0%], a change in resonance band due to the thickness variation can be  
10 reduced. Therefore, taking the thickness variation into consideration, the thickness of the low acoustic impedance layer 103b is preferably in the range of [the ideal length  $\lambda/4$  minus 20.0%] to [the ideal length  $\lambda/4$  minus 1.0%].

Within the range of [the ideal length  $\lambda/4$  minus 20.0%] to  
15 [the ideal length  $\lambda/4$  minus 1.0%], the most preferable thickness of the low acoustic impedance layer 103b varies depending on conditions of the piezoelectric thin film vibrator 109b.

FIG. 3 is a diagram for explaining how the most preferable thickness of the low acoustic impedance layer 103b varies depending  
20 on the conditions of the piezoelectric thin film vibrator 109b.

In FIG. 3, it is assumed that the piezoelectric thin film 105b is made of aluminum nitride (AlN), the lower electrode 104b and the upper electrode 106b are made of molybdenum (Mo), the thickness of the piezoelectric thin film 105b is fixed  
25 to 2.0  $\mu\text{m}$ , and the thicknesses of the lower electrode 104b and

the upper electrode 106b are set to be 0.01  $\mu\text{m}$ , 0.2  $\mu\text{m}$  or 0.5  $\mu\text{m}$ . In this case, resonance bands  $\Delta f$  obtained by changing the thickness of the low acoustic impedance layer 103b are compared.

Typically, when an electrode material is deposited by a process technique, such as sputtering or the like, the thinnest thickness of an electrode is considered to be about 0.01  $\mu\text{m}$ . In the case of this value, when the thickness of the low acoustic impedance layer 103b is [the ideal length  $\lambda/4$  minus about 1%], the resonance band  $\Delta f$  becomes larger than when the thickness is the ideal length  $\lambda/4$ .

Therefore, as can be seen from FIG. 3, the most preferable thickness of the low acoustic impedance layer 103b is included in the range of [the ideal length  $\lambda/4$  minus 20.0%] to [the ideal length  $\lambda/4$  minus 1.0%], no matter that the piezoelectric thin film vibrator is constructed with any settings.

Next, a description will be given of why the thickness of the low acoustic impedance layer 103b is preferably smaller than the ideal length  $\lambda/4$ .

In the thin film bulk acoustic resonator which utilizes the acoustic mirror, the piezoelectric thin film 105b generally resonates with a frequency corresponding to a wavelength of  $\lambda/2$ . However, the thicknesses of the lower electrode 104b and the upper electrode 106b are significantly large with respect to the thickness of the piezoelectric thin film 105b. The thicknesses of the upper and lower electrodes have an influence on a vibration

distribution.

Since the piezoelectric thin film vibrator 109b is deposited on the acoustic mirror layer 108b, the mass load thereof is applied to the low acoustic impedance layer 103b and the high acoustic impedance layer 102b. The mass load has an influence on a vibration distribution in the acoustic mirror layer.

According to the above-described two factors, the vibration distribution in each acoustic mirror layer substantially deviates from the ideal  $\lambda/4$  vibration distribution. Therefore, it will be understood that an optimum thickness of the low acoustic impedance layer 103b is smaller than the ideal length  $\lambda/4$ .

Thus, according to the first embodiment, by setting the thickness of the low acoustic impedance layer of the acoustic mirror layers in the acoustic mirror type thin film bulk acoustic resonator to be smaller than the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator, the resonance bandwidth can be broadened. By broadening the resonance bandwidth, it is possible to prevent a degradation in resonance characteristics due to variations in the thickness of the low acoustic impedance layer.

Although the thickness of each low acoustic impedance layer is smaller than the ideal length  $\lambda/4$  in the first embodiment, a similar effect can be obtained if at least one low acoustic impedance layer has a thickness which is lower than the ideal length  $\lambda/4$ .



Also, in the first embodiment, a low acoustic impedance layer is provided immediately below the lower electrode, and therebelow, high acoustic impedance layer(s) and low acoustic impedance layer(s) are alternately provided. Alternatively, a high acoustic impedance layer may be provided immediately below the lower electrode, and therebelow, low acoustic impedance layer(s) and high acoustic impedance layer(s) may be alternately provided.

(Second embodiment)

FIG. 4 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a second embodiment of the present invention. In FIG. 4, the acoustic mirror type thin film bulk acoustic resonator 207b comprises a substrate 101b, high acoustic impedance layers 202b, low acoustic impedance layers 203b, a lower electrode 104b, a piezoelectric thin film 105b, and an upper electrode 106b. In FIG. 4, the same parts as those of the first embodiment are referenced with the same reference numerals and will not be explained.

The number of the high acoustic impedance layers 202b is two in FIG. 4, or alternatively, may be one, or three or more. Also, the number of the low acoustic impedance layers 203b is two in FIG. 4, or alternatively, may be one, or three or more. Note that an uppermost one of the low acoustic impedance layers 203b is formed immediately below the lower electrode 104b. The low acoustic impedance layers 203b and the high acoustic impedance layers 202b are alternately formed in the same number.

An acoustic mirror layer 208b, which is composed of the high acoustic impedance layers 202b and the low acoustic impedance layers 203b, is provided on the substrate 101b. On the acoustic mirror layer 208b, a piezoelectric thin film vibrator 109b, which  
5 is composed of the lower electrode 104b, the piezoelectric thin film 105b and the upper electrode 106b, is provided.

The high acoustic impedance layer 202b is made of a high acoustic impedance material, such as tungsten (W), molybdenum (Mo) or the like. A thickness (B1) of the high acoustic impedance  
10 layer 202b is equal to a thickness which maximizes a bandwidth of resonance characteristics. The present inventors found that the thickness (B1) of the high acoustic impedance layer 202b which maximizes the bandwidth of the resonance characteristics is smaller than the size of one fourth of an acoustic wavelength calculated  
15 from a resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

The low acoustic impedance layer 203b is made of a low acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or the like. A thickness (A) of the low acoustic impedance layer 203b  
20 is equal to the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

In a production process of the acoustic mirror type thin film bulk acoustic resonator 207b, the thickness of each acoustic  
25 mirror layer varies in one chip due to an influence of surface

roughness of the substrate 101b, the low acoustic impedance layer 203b, and the high acoustic impedance layer 202b.

In addition, film forming conditions vary depending on a position on a wafer, resulting in variations in chip. Due to an  
5 influence of the chip variation, the thickness of each acoustic mirror layer varies among a plurality of chips.

The magnitude of the variation is about 1% at maximum with respect to the thickness.

Therefore, the thickness (B1) of the high acoustic impedance  
10 layer 202b is preferably lower by 1% or more than one fourth of the acoustic wavelength calculated from the resonant frequency in free space of the piezoelectric thin film vibrator 109b, taking its variations into consideration.

FIG. 5 is a graph showing a change in resonance band when  
15 the thickness of the high acoustic impedance layer 202b is changed while fixing the other values. Here, it is assumed that the lower electrode 104b is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ , the piezoelectric thin film 105b is made of aluminum nitride and has a thickness of 2.0  $\mu\text{m}$ , and the upper electrode 106b  
20 is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ .

In FIG. 5, the horizontal axis represents a value obtained by standardizing the thickness of the high acoustic impedance layer 202b using the ideal length  $\lambda/4$ . The vertical axis represents a value obtained by standardizing a change in a resonance  
25 bandwidth using a bandwidth ( $\Delta f$ ) which is obtained when the

thickness of the high acoustic impedance layer 202b is equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thickness of the high acoustic impedance layer 202b is equal to the ideal  
5 length  $\lambda/4$ .

As can be seen from FIG. 5, the thickness of the high acoustic impedance layer 202b which maximizes the resonance bandwidth is obtained at a thickness point Y which is smaller than a thickness point X corresponding to the ideal length  $\lambda/4$ . Therefore, the  
10 thickness of the high acoustic impedance layer 202b is preferably smaller than the size of one fourth of the acoustic wavelength which is calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

15 For example, the degree of a change in resonance bandwidth at the point X is compared with the degree of a change in resonance bandwidth at the point Y, assuming that there is, for example, a variation of  $\pm 1\%$  in thickness. In this case, it will be found that the change degree is smaller at the point Y than at the point X.  
20 Therefore, when the thickness at the point Y is determined to be the thickness (B1) of the high acoustic impedance layer 202b, a change in resonance band due to a variation in thickness can be further reduced. Thereby, an influence of the thickness variation can be minimized.

25 Also, as can be seen from FIG. 5, when the thickness of the

high acoustic impedance layer 202b is more than 0.8 times the length  $\lambda/4$ , i.e., more than [the ideal length  $\lambda/4$  minus 20.0%], a change in resonance band due to the thickness variation can be reduced. Therefore, taking the thickness variation into  
5 consideration, the thickness of the high acoustic impedance layer 202b is preferably in the range of [the ideal length  $\lambda/4$  minus 20.0%] to [the ideal length  $\lambda/4$  minus 1.0%].

The principle of why the thickness of the high acoustic impedance layer 202b is preferably smaller than the size of one  
10 fourth of the acoustic wavelength which is calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b, is similar to that of the first embodiment.

Thus, according to the second embodiment, by setting the  
15 thickness of the high acoustic impedance layer of the acoustic mirror layers in the acoustic mirror type thin film bulk acoustic resonator to be smaller than the size of one fourth of an acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator,  
20 the resonance bandwidth can be broadened. By broadening the resonance bandwidth, it is possible to prevent a degradation in resonance characteristics due to variations in the thickness of the high acoustic impedance layer.

Although the thickness of each high acoustic impedance layer  
25 is smaller than the ideal length  $\lambda/4$  in the second embodiment,

a similar effect can be obtained if at least one high acoustic impedance layer has a thickness which is lower than the ideal length  $\lambda/4$ .

Also, in the second embodiment, a low acoustic impedance layer is provided immediately below the lower electrode, and therebelow, high acoustic impedance layer(s) and low acoustic impedance layer(s) are alternately provided. Alternatively, a high acoustic impedance layer may be provided immediately below the lower electrode, and therebelow, low acoustic impedance layer(s) and high acoustic impedance layer(s) may be alternately provided.

(Third embodiment)

FIG. 6 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a third embodiment of the present invention. In FIG. 6, the acoustic mirror type thin film bulk acoustic resonator 307b comprises a substrate 101b, high acoustic impedance layers 302b, low acoustic impedance layers 303b, a lower electrode 104b, a piezoelectric thin film 105b, and an upper electrode 106b. In FIG. 6, the same parts as those of the first embodiment are referenced with the same reference numerals and will not be explained.

The number of the high acoustic impedance layers 302b is two in FIG. 6, or alternatively, may be one, or three or more. Also, the number of the low acoustic impedance layers 303b is two in FIG. 6, or alternatively, may be one, or three or more. Note

that an uppermost one of the low acoustic impedance layers 303b is formed immediately below the lower electrode 104b. The low acoustic impedance layers 303b and the high acoustic impedance layers 302b are alternately formed in the same number.

5        An acoustic mirror layer 308b, which is composed of the high acoustic impedance layers 302b and the low acoustic impedance layers 303b, is provided on the substrate 101b. On the acoustic mirror layer 308b, a piezoelectric thin film vibrator 109b, which is composed of the lower electrode 104b, the piezoelectric thin  
10 film 105b and the upper electrode 106b, is provided.

      The high acoustic impedance layer 302b is made of a high acoustic impedance material, such as tungsten (W), molybdenum (Mo) or the like. A thickness (B2) of the high acoustic impedance layer 302b is smaller than the size of one fourth of an acoustic  
15 wavelength calculated from a resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

      The low acoustic impedance layer 303b is made of a low acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or  
20 the like. A thickness (A2) of the low acoustic impedance layer 303b is smaller than the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

      In a production process of the acoustic mirror type thin  
25 film bulk acoustic resonator 307b, the thickness of each acoustic

mirror layer varies in one chip due to an influence of surface roughness of the substrate 101b, the low acoustic impedance layer 303b, and the high acoustic impedance layer 302b.

In addition, film forming conditions vary depending on a position on a wafer, resulting in variations in chip. Due to an influence of the chip variation, the thickness of each acoustic mirror layer varies among a plurality of chips.

The magnitude of the variation is about 1% at maximum with respect to the thickness.

Therefore, the thickness (A2) of the low acoustic impedance layer 303b and the thickness (B2) of the high acoustic impedance layer 302b are each preferably lower by 1% or more than one fourth of the acoustic wavelength calculated from the resonant frequency in free space of the piezoelectric thin film vibrator 109b, taking their variations into consideration.

FIG. 7 is a graph showing a change in resonance band when the thickness of the high acoustic impedance layer 302b and the thickness of the low acoustic impedance layer 303b are simultaneously changed at the same rate. Here, it is assumed that the lower electrode 104b is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ , the piezoelectric thin film 105b is made of aluminum nitride and has a thickness of 2.0  $\mu\text{m}$ , and the upper electrode 106b is made of molybdenum (Mo) and has a thickness of 0.2  $\mu\text{m}$ .

In FIG. 7, the horizontal axis represents a value obtained



by standardizing the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b using the ideal length  $\lambda/4$ . The vertical axis represents a value obtained by standardizing a change in a resonance bandwidth using a bandwidth  
5  $(\Delta f)$  which is obtained when the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thicknesses of the high acoustic impedance layer 302b  
10 and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ .

As can be seen from FIG. 7, the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b which maximize the resonance bandwidth is obtained at  
15 a thickness point Y which is smaller than a thickness point X corresponding to the ideal length  $\lambda/4$ . Therefore, the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each preferably smaller than the size of one fourth of the acoustic wavelength which is calculated  
20 from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

For example, the degree of a change in resonance bandwidth at the point X is compared with the degree of a change in resonance bandwidth at the point Y, assuming that there is, for example,  
25 a variation of  $\pm 1\%$  in thickness. In this case, it will be found

that the change degree is smaller at the point Y than at the point X.  
Therefore, when the thickness at the point Y is determined to be  
the thicknesses (A2, B2) of the high acoustic impedance layer 302b  
and the low acoustic impedance layer 303b, a change in resonance  
5 band due to a variation in thickness can be further reduced.  
Thereby, an influence of the thickness variation can be minimized.

Also as can be seen from FIG. 7, the optimum thicknesses  
of the high acoustic impedance layer 302b and the low acoustic  
impedance layer 303b are each preferably in the range of [the ideal  
10 length  $\lambda/4$  minus 20.0%] to [the ideal length  $\lambda/4$  minus 1.0%].

The principle of why the thicknesses of the high acoustic  
impedance layer 302b and the low acoustic impedance layer 303b  
are each preferably smaller than the size of one fourth of the  
acoustic wavelength which is calculated from the resonant frequency  
15 (antiresonant frequency) in free space of the piezoelectric thin  
film vibrator 109b, is similar to that of the first embodiment.

Further, the present inventors found that the effect of the  
present invention is obtained to a further extent with an increase  
in the thicknesses of the upper and lower electrodes. FIG. 8 is  
20 a graph for explaining that the effect of the present invention  
is obtained to a further extent with an increase in the thicknesses  
of the upper and lower electrodes.

In FIG. 8, the thicknesses of the high acoustic impedance  
layer 302b and the low acoustic impedance layer 303b are changed  
25 simultaneously at the same rate, and resonance bands  $\Delta f$  are compared

when the thickness of the lower electrode 104b made of molybdenum (Mo) and the thickness of the upper electrode 106b made of molybdenum (Mo) are simultaneously changed to  $1.25 \times 10^{-4}$  times, 0.25 times or 0.63 times the acoustic wavelength calculated from the resonant frequency.

In FIG. 8, the horizontal axis represents a value obtained by standardizing the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b using the ideal length  $\lambda/4$ . The vertical axis represents a value obtained by standardizing a change in a resonance bandwidth using a bandwidth ( $\Delta f$ ) which is obtained when the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ .

As can be seen from FIG. 8, when the thicknesses of the lower electrode 104b and the upper electrode 106b are increased, the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b when the resonance bandwidth is maximum, are smaller than the ideal length  $\lambda/4$ . Further, it was found that the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b when the resonance bandwidth is maximum, are even smaller than the ideal

length  $\lambda/4$  as the thicknesses of the lower electrode 104b and the upper electrode 106b are increased. It was also found that the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b when the resonance bandwidth is maximum, are in the range of [the ideal length  $\lambda/4$  minus 40%] to [the ideal length  $\lambda/4$  minus 1.0%].

Further, the present inventors found that, the effect of the present invention is obtained to a further extent with an increase in the ratio of the acoustic impedance of the high acoustic impedance layer 302b to the acoustic impedance of the low acoustic impedance layer 303b (the acoustic impedance of the high acoustic impedance layer 302b  $\div$  the acoustic impedance of the low acoustic impedance layer 303b). FIG. 9 is a graph showing for explaining that the effect of the present invention is obtained to a further extent with an increase in the ratio of the acoustic impedance of the high acoustic impedance layer 302b to the acoustic impedance of the low acoustic impedance layer 303b.

In FIG. 9, the thickness of the high acoustic impedance layer 302b and the thickness of the low acoustic impedance layer 303b are changed simultaneously at the same rate. The results of the following three cases are compared: a ratio  $Z_h/Z_l$  of an acoustic impedance  $Z_h$  of the high acoustic impedance layer 302b to an acoustic impedance  $Z_l$  of the low acoustic impedance layer 303b in the acoustic mirror layer is 2.21 (the high acoustic impedance layer 302b is made of AlN and the low

acoustic impedance layer 303b is made of Mo); the ratio  $Z_h/Z_l$  is 3.46 (the high acoustic impedance layer 302b is made of  $\text{SiO}_2$  and the low acoustic impedance layer 303b is made of Mo); and the ratio  $Z_h/Z_l$  is 4.82 (the high acoustic impedance layer 302b is made of  $\text{SiO}_2$  and the low acoustic impedance layer 303b is made of W).

In FIG. 9, the horizontal axis represents a value obtained by standardizing the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b using the ideal length  $\lambda/4$ . The vertical axis represents a value obtained by standardizing a change in a resonance bandwidth using a bandwidth ( $\Delta f$ ) which is obtained when the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b are each equal to the ideal length  $\lambda/4$ .

As can be seen from FIG. 9, it was found that as the acoustic impedance ratio is increased, the rate of a degradation in resonance band with respect to a change in the thicknesses of the high acoustic impedance layer 302b and the low acoustic impedance layer 303b, is reduced.

Thus, according to the third embodiment, by selecting materials for the high acoustic impedance layer and the low acoustic impedance layer so that their acoustic impedance ratio is high

and determining the thicknesses of the high acoustic impedance layer and the low acoustic impedance layer at the point Y which maximizes the resonance band, it is possible to ~~minize~~minimize a degradation in resonance band due to a variation in the thickness.

5           In the third embodiment, a low acoustic impedance layer is provided immediately below the lower electrode, and therebelow, high acoustic impedance layer(s) and low acoustic impedance layer(s) are alternately provided. Alternatively, a high acoustic impedance layer may be provided immediately below the  
10 lower electrode, and therebelow, low acoustic impedance layer(s) and high acoustic impedance layer(s) may be alternately provided.

(Fourth embodiment)

FIG. 10 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a fourth embodiment  
15 of the present invention. In FIG. 10, the acoustic mirror type thin film bulk acoustic resonator 407b comprises a substrate 101b, high acoustic impedance layers 102b, an uppermost low acoustic impedance layer 403b, a low acoustic impedance layer 403c, a lower electrode 104b, a piezoelectric thin film 105b, and an upper  
20 electrode 106b. In FIG. 10, the same parts as those of the first embodiment are referenced with the same reference numerals and will not be explained.

The number of the high acoustic impedance layers 102b is two in FIG. 10, or alternatively, may be three or more. Also,  
25 the total number of the uppermost low acoustic impedance layer 403b

and the low acoustic impedance layer 403c is two in FIG. 10, or alternatively, may be three or more. Note that an uppermost one of the low acoustic impedance layers 403b is formed immediately below the lower electrode 104b.

5           An acoustic mirror layer 408b, which is composed of the high acoustic impedance layers 102b, the uppermost low acoustic impedance layer 403b and the low acoustic impedance layers 403c, is provided on the substrate 101b. On the acoustic mirror layer 408b, a piezoelectric thin film vibrator 109b, which is  
10       composed of the lower electrode 104b, the piezoelectric thin film 105b and the upper electrode 106b, is provided.

          The uppermost low acoustic impedance layer 403b is made of a low acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or the like. A thickness ( $A_3$ ) of the uppermost low acoustic  
15       impedance layer 403b is smaller than the size of one fourth of an acoustic wavelength calculated from a resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

          The low acoustic impedance layer 403c is made of a low  
20       acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or the like. A thickness ( $A$ ) of the low acoustic impedance layer 403c is equal to the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

25           FIG. 11 is a graph showing a change in resonance band when

the thickness of the uppermost low acoustic impedance layer 403b is changed while fixing the other values. In FIG. 11, the horizontal axis represents a value obtained by standardizing the thickness of the uppermost acoustic impedance layer 403b using the ideal length  $\lambda/4$ . The vertical axis represents a value obtained by standardizing a change in a resonance bandwidth using a bandwidth ( $\Delta f$ ) which is obtained when the thickness of the uppermost acoustic impedance layer 403b is equal to the ideal length  $\lambda/4$ . On the horizontal axis and the vertical axis, a value of 1 is a value which is obtained when the thickness of the high acoustic impedance layer 202b is equal to the ideal length  $\lambda/4$ .

As can be seen from FIG. 11, the thickness of the uppermost acoustic impedance layer 403b which maximizes the resonance bandwidth is obtained at a thickness point Y which is smaller than a thickness point X corresponding to the ideal length  $\lambda/4$ . Therefore, the thickness of the uppermost acoustic impedance layer 403b is preferably smaller than the size of one fourth of the acoustic wavelength which is calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b.

For example, the degree of a change in resonance bandwidth at the point X is compared with the degree of a change in resonance bandwidth at the point Y, assuming that there is, for example, a variation of  $\pm 1\%$  in thickness. In this case, it will be found that the change degree is smaller at the point Y than at the point X.



Therefore, when the thickness at the point Y is determined to be the thickness (A3) of the uppermost acoustic impedance layer 403b, a change in resonance band due to a variation in thickness can be further reduced. Thereby, an influence of the thickness  
5 variation can be minimized.

Also, as can be seen from FIG. 11, the thickness of the uppermost acoustic impedance layer 403b is preferably in the range of [the ideal length  $\lambda/4$  minus 20.0%] to [the ideal length  $\lambda/4$  minus 1.0%].

10 The principle of why the thickness of the uppermost acoustic impedance layer 403b is preferably smaller than the size of one fourth of the acoustic wavelength which is calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 109b, is similar to that of the  
15 first embodiment.

Thus, according to the second embodiment, by setting the thickness of the uppermost low acoustic impedance layer of the acoustic mirror layers in the acoustic mirror type thin film bulk acoustic resonator to be smaller than the size of one fourth of  
20 an acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator, the resonance bandwidth can be broadened. By broadening the resonance bandwidth, it is possible to prevent a degradation in resonance characteristics due to variations in the  
25 thickness of the uppermost low acoustic impedance layer.

(Fifth embodiment)

FIG. 12 is a cross-sectional view of an acoustic mirror type thin film bulk acoustic resonator according to a fifth embodiment of the present invention. In FIG. 12, the acoustic mirror type  
5 thin film bulk acoustic resonator 507b comprises a substrate 101b, high acoustic impedance layers 502b, low acoustic impedance layers 503b, a lower electrode 504b, a piezoelectric thin film 105b, and an upper electrode 506b. In FIG. 12, the same parts as those of the first embodiment are referenced with the same  
10 reference numerals and will not be explained.

The number of the high acoustic impedance layers 502b is two in FIG. 12, or alternatively, may be one, or three or more. Also, the number of the low acoustic impedance layers 503b is two in FIG. 12, or alternatively, may be one, or three or more. Note  
15 that an uppermost one of the low acoustic impedance layers 503b is formed immediately below the lower electrode 504b. The low acoustic impedance layers 503b and the high acoustic impedance layers 502b are alternately formed in the same number.

An acoustic mirror layer 508b, which is composed of the high  
20 acoustic impedance layers 502b and the low acoustic impedance layers 503b, is provided on the substrate 101b. On the acoustic mirror layer 508b, a piezoelectric thin film vibrator 509b, which is composed of the lower electrode 504b, the piezoelectric thin film 105b and the upper electrode 506b, is provided.

25 The low acoustic impedance layer 503b is made of a low

acoustic impedance material, such as silicon dioxide ( $\text{SiO}_2$ ) or the like. A thickness (A4) of the low acoustic impedance layer 503b is smaller than, larger than, or equal to the size of one fourth of an acoustic wavelength calculated from a resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 509b.

The high acoustic impedance layer 502b is made of a high acoustic impedance material, such as tungsten (W), molybdenum (Mo) or the like. A thickness (B) of the high acoustic impedance layer 502b is smaller than, larger than, or equal to the size of one fourth of the acoustic wavelength calculated from the resonant frequency (antiresonant frequency) in free space of the piezoelectric thin film vibrator 509b.

The lower electrode 504b is made of, for example, molybdenum (Mo), aluminum (Al), platinum (Pt), gold (Au) or the like.

The upper electrode 506b is made of, for example, molybdenum (Mo), aluminum (Al), platinum (Pt), gold (Au), or the like.

A thickness (C) of the lower electrode 504b is larger than a thickness (D) of the upper electrode 506b. In other words,  $C/D > 1.0$ . Hereinafter, the ratio (C/D) of the thickness of the lower electrode 504b to the thickness of the upper electrode 506b is referred to as an "upper/lower ratio".

The present inventors studied what proportion of the sum (C+D) of the thickness (C) of the lower electrode 504b and the thickness (D) of the upper electrode 506b with respect to the whole

thickness  $(C+D+E)$  of the piezoelectric thin film vibrator 509b, can broaden the resonance bandwidth. The proportion is represented as  $(C+D)/(C+D+E)$ . Hereinafter, the proportion  $(C+D)/(C+D+E)$  is referred to as an electrode ratio.

5           FIG. 13 is a graph showing a band ratio when the electrode ratio is 10%. In FIG. 13, the horizontal axis represents a thickness of the low acoustic impedance layer 503b as a correction amount from the ideal length  $\lambda/4$ . On the horizontal axis, "0" indicates when the low acoustic impedance layer 503b has a  
10 thickness of  $\lambda/4$ . On the horizontal axis, "-10", "-20" and "-30" indicate when the low acoustic impedance layer 503b has a thickness of  $[\lambda/4 \text{ minus } 10\%, 20\% \text{ and } 30\%]$ , respectively. On the horizontal axis, "10" and "20" indicate when the low acoustic impedance layer 503b has a thickness of  $[\lambda/4 \text{ plus } 10\% \text{ and } 20\%]$ , respectively.  
15 The vertical axis represents a band ratio. The band ratio is a ratio  $(\Delta f/f_r)$  of a bandwidth  $\Delta f$  to a resonant frequency  $f_r$ . If the resonant frequency  $f_r$  is assumed to be constant, the larger the band ratio, the larger the bandwidth  $\Delta f$ . In FIG. 13, a dashed line indicates when the thickness (C) of the lower electrode is  
20 equal to the thickness (D) of the upper electrode as in the first to fourth embodiments, i.e., the ratio  $(C/D)$  of the thickness of the lower electrode to the thickness of the upper electrode is 1.0. A solid line indicates when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode, i.e.,  
25  $C/D$  is 1.5.

When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is larger by 5% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 13, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode, if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 5%] to [the ideal length  $\lambda/4$  plus 12%].

Therefore, preferably, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is increased, the band ratio can be increased.

FIG. 14 is a graph showing a band ratio when the electrode

ratio is 14%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is larger by 4% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 14, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 11%] to [the ideal length  $\lambda/4$  plus 12%].

FIG. 15 is a graph showing a band ratio when the electrode ratio is 20%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is larger by 1.5% than the ideal length  $\lambda/4$  (see a point P). On

the other hand, when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 15, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 17%] to [the ideal length  $\lambda/4$  plus 12%].

FIG. 16 is a graph showing a band ratio when the electrode ratio is 30%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is smaller by 2.5% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see

a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 16, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 25%] to [the ideal length  $\lambda/4$  plus 12%].

Therefore, preferably, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is decreased, the band ratio can be increased.

FIG. 17 is a graph showing a band ratio when the electrode ratio is 40%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is smaller by 5% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.35 times the thickness of the upper electrode ( $C/D=1.35$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see



a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 17, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 27%] to [the ideal length  $\lambda/4$  plus 9%].

Therefore, preferably, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is decreased, the band ratio can be increased.

FIG. 18 is a graph showing a band ratio when the electrode ratio is 50%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is smaller by 9% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.3 times the thickness of the upper electrode ( $C/D=1.3$ ), the band ratio is larger than when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  (see

a point Q). Therefore, when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode without adjustment of the thickness of the low acoustic impedance layer, the band ratio is larger than when only the thickness of the low acoustic impedance layer is optimized.

As can be seen from FIG. 18, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 28%] to [the ideal length  $\lambda/4$  plus 5%].

Therefore, preferably, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is decreased, the band ratio can be increased.

FIG. 19 is a graph showing a band ratio when the electrode ratio is 60%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is smaller by 11% than the ideal length  $\lambda/4$  (see a point P). On the other hand, when the thickness of the lower electrode is 1.22 times the thickness of the upper electrode ( $C/D=1.22$ ), the band ratio is about the same as when  $C/D=1.0$  even if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$

(see a point Q). Therefore, the effect obtained only when the thickness of the lower electrode is set to be larger than the thickness of the upper electrode, is no longer obtained if the band ratio is larger than 60%.

5           However, as can be seen from FIG. 19, when the thickness of the lower electrode is larger than the thickness of the upper electrode, the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode if the thickness of the low acoustic impedance layer is in the  
10   range of [the ideal length  $\lambda/4$  minus 28%] to [the ideal length  $\lambda/4$  plus 0%]. Therefore, preferably, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is decreased, the band ratio can be increased.

15           FIG. 20 is a graph showing a band ratio when the electrode ratio is 70%. When the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is smaller by 14% than the ideal length  $\lambda/4$  (see a point P). On  
20   the other hand, when the thickness of the lower electrode is 1.15 times the thickness of the upper electrode ( $C/D=1.15$ ), the band ratio obtained when the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$  is smaller than the maximum band ratio obtained when  $C/D=1.0$  (see a point Q). Therefore, when  
25   the electrode ratio is 70%, the band ratio cannot be increased

only by setting the thickness of the lower electrode to be larger than the thickness of the upper electrode. However, as can be seen from FIG. 20, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is in the range of [the ideal length  $\lambda/4$  minus 28%] to [the ideal length  $\lambda/4$  minus 5%], the band ratio is larger than when the thickness of the lower electrode is equal to the thickness of the upper electrode. Therefore, it will be understood that, when the thickness of the lower electrode is larger than the thickness of the upper electrode and the thickness of the low acoustic impedance layer is decreased, the band ratio can be increased.

FIG. 21 is a graph showing a band ratio when the electrode ratio is 80%. In the graph of FIG. 21, when the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ), the band ratio is maximum if the thickness of the low acoustic impedance layer is equal to [the ideal length  $\lambda/4$  minus 15%] (see a point P). On the other hand, when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ) or 0.8 times ( $C/D=0.8$ ), a band ratio larger than when  $C/D=1.0$  cannot be obtained if the thickness of the low acoustic impedance layer is equal to the ideal length  $\lambda/4$ . Therefore, when the electrode ratio is 80%, the band ratio cannot be increased only by setting the thickness of the lower electrode to be larger or smaller than the thickness of the upper electrode (see points P

and  $Q$ ).

As shown in FIG. 21, when the thickness of the lower electrode is larger than the thickness of the upper electrode or when the thickness of the lower electrode is smaller than the thickness of the upper electrode, conditions under which a band ratio exceeding the maximum ratio when  $C/D=1.0$  cannot be obtained even if the thickness of the low acoustic impedance layer is adjusted. Therefore, when the electrode ratio is 80%, the band ratio cannot be increased by setting the thickness of the lower electrode to be larger or smaller than the thickness of the upper electrode. However, by setting the thickness of the lower electrode to be equal to the thickness of the upper electrode and adjusting the thickness of the low acoustic impedance layer, the band ratio can be increased. Therefore, an upper limit value of the electrode ratio is estimated to be 80%.

FIG. 22 is a graph showing an optimum value of the upper/lower ratio. In FIG. 22, the horizontal axis represents the electrode ratio. The vertical axis represents an optimum value of the upper/lower ratio when the electrode ratio indicated by the horizontal axis is used. The optimum value of the upper/lower ratio indicated by the vertical axis is an upper/lower ratio which can provide a maximum band ratio by adjusting the thickness of the low acoustic impedance layer. For example, as shown in FIG. 20, when the electrode ratio is 70%, by setting the upper/lower ratio to be 1.15 and the thickness of the low acoustic impedance layer

to be [the ideal length  $\lambda/4$  minus about 15%], a maximum band ratio can be obtained. In FIG. 22, the upper/lower ratio thus set is shown. In FIG. 22, maximum values of the upper/lower ratio are plotted with diamonds, which are obtained when the electrode ratio is 10%, 14%, 20%, 30%, 40%, 50%, 60%, 70% and 80%, respectively, and a curve interpolates between each diamond.

As shown in FIG. 22, when the electrode ratio is 80%, the optimum upper/lower ratio is 1.0. According to FIGS. 21 and 22, it will be understood that, when the electrode ratio is 80%, the band ratio cannot be increased by adjusting the thickness of the lower electrode. However, however, the band ratio can be increased by setting the thickness of the lower electrode to be equal to the thickness of the upper electrode and adjusting the thickness of the low acoustic impedance layer. Therefore, when the electrode ratio is 60% or more and less than 80%, the band ratio cannot be increased only by adjusting the thickness of the lower electrode. However, however, the band ratio can be increased by setting the thickness of the lower electrode to be thicker than the upper electrode and adjusting the thickness of the low impedance layer.

FIG. 23 is a graph showing a band ratio when the electrode ratio is 5%. In FIG. 23, a band ratio obtained when the thickness of the upper electrode is equal to the thickness of the lower electrode ( $C/D=1.0$ ) and a band ratio obtained when the thickness of the lower electrode is 1.5 times the thickness of the upper electrode ( $C/D=1.5$ ), are shown. In the case of  $C/D=1.0$ , the band

ratio is maximum when the thickness of the low acoustic impedance layer is [the ideal length  $\lambda/4$  plus 9%] (see a point P). Similarly, in the case of  $C/D=1.5$ , the band ratio is maximum when the thickness of the low acoustic impedance layer is [the ideal length  $\lambda/4$  plus 9%] (see a point P). Therefore, when the electrode ratio is 5% and  $C/D$  is 1.5, there are no conditions under which a maximum band ratio exceeds that obtained when  $C/D=1.0$ . Therefore, when the electrode ratio is 5%, the band ratio cannot be increased by increasing the lower electrode or adjusting the thickness of the low acoustic impedance layer. Therefore, the lower limit of the electrode ratio is estimated to be 5%.

According to the first to fifth embodiments, it will be understood as follows.

As shown with the points Q in FIGS. 13 to 19 and the points P in FIG. 23, in the piezoelectric thin film vibrator, the sum of the thickness of the lower electrode and the thickness of the upper electrode is between 5% or more and 60% or less of the thickness of the piezoelectric thin film vibrator and the thickness of the lower electrode is larger than the thickness of the upper electrode. In this case, the thin film bulk acoustic resonator has a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

As shown with the points Q in FIGS. 13 to 19 and the points P in FIG. 23, in the case where the electrode ratio is between 5%

~~or more~~ and 60% ~~or less~~, even when all the low acoustic impedance layers have a thickness of  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. In this case, as shown in FIG. 11 in the fourth embodiment, it is estimated that, even when only the uppermost low acoustic impedance layer has a thickness of  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

As shown in FIGS. 13 to 19, in the case where the electrode ratio is between 5% ~~or more~~ and 60% ~~or less~~, even when all the low acoustic impedance layers have a thickness of less than  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. As shown in FIGS. 15 to 19, by setting the thickness of the low acoustic impedance layer to be less than  $\lambda/4$ , a band ratio which is higher than when the thickness of the low acoustic impedance layer is equal to  $\lambda/4$ , may be obtained. In this case, as shown in FIG. 11 in the fourth embodiment, it is estimated that, even when only the uppermost low acoustic impedance layer has a thickness of less than  $\lambda/4$ ,



it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

5           As shown in FIGS. 13 to 19, in the case where the electrode ratio is between 5% or more and 60% or less, even when all the low acoustic impedance layers have a thickness of more than  $\lambda/4$ , it is possible obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic  
10 resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. As shown in FIG. 13, by setting the thickness of the low acoustic impedance layer to be more than  $\lambda/4$ , a band ratio which is higher than when the thickness of the low acoustic impedance layer is equal to  $\lambda/4$ , may be obtained.  
15 In this case, it is estimated that, even when only the uppermost low acoustic impedance layer has a thickness of more than  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal  
20 to the thickness of the upper electrode.

          In the examples of FIGS. 13 to 16, the thickness of the low acoustic impedance layer is adjusted. However, when the electrode ratio is between 5% or more and 60% or less and the thickness of the lower electrode is larger than the thickness of the upper  
25 electrode, by setting the thickness of the high acoustic impedance

layer to be less than  $\lambda/4$  as in the second embodiment, it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. Further, according to the example of FIG. 13, by setting the thickness of the high acoustic impedance layer to be more than  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. Therefore, even when the thickness of the high acoustic impedance layer is different from  $\lambda/4$ , it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode. It will be understood from the third embodiment that, when the thickness of the high acoustic impedance layer is different from  $\lambda/4$ , the thickness of the low acoustic impedance layer may be different from  $\lambda/4$ . In this case, at least the uppermost low acoustic impedance layer may have a thickness different from  $\lambda/4$ .

According to FIG. 13, in the case where the electrode ratio is 10%, if the upper/lower ratio is 1.5 and the thickness of the low acoustic impedance layer is between [ $\lambda/4$  minus 5%] (inclusive) and [ $\lambda/4$  plus 12%] (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained

in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 14, in the case where the electrode ratio is 14%, if the upper/lower ratio is 1.5 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 11\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 12\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 15, in the case where the electrode ratio is 20%, if the upper/lower ratio is 1.5 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 17\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 12\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

As shown in FIGS. 14 and 15, in a thin film bulk acoustic resonator having an electrode ratio of 14% to 20%, the band ratio can be set to be 0.0208 or more by adjusting the thickness of the low acoustic impedance layer. Thus, a preferable band ratio can be obtained.

According to FIG. 16, in the case where the electrode ratio is 30%, if the upper/lower ratio is 1.5 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 25\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 12\%]$  (inclusive), it is possible to obtain a band

ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 17, in the case where the electrode ratio is 40%, if the upper/lower ratio is 1.35 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 27\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 9\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 18, in the case where the electrode ratio is 50%, if the upper/lower ratio is 1.3 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 28\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 5\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 19, in the case where the electrode ratio is 60%, if the upper/lower ratio is 1.22 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 28\%]$  (inclusive) and  $[\lambda/4 \text{ plus } 0\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 20, in the case where the electrode ratio

is 70%, if the upper/lower ratio is 1.15 and the thickness of the low acoustic impedance layer is between  $[\lambda/4 \text{ minus } 28\%]$  (inclusive) and  $[\lambda/4 \text{ minus } 5\%]$  (inclusive), it is possible to obtain a band ratio which is larger than or equal to a maximum band ratio obtained in a thin film bulk acoustic resonator in which the thickness of the lower electrode is equal to the thickness of the upper electrode.

According to FIG. 21, in the case where the electrode ratio is 80%, if the upper/lower ratio is 1.0 and the thickness of the low acoustic impedance layer is adjusted to be larger or smaller than the ideal length  $\lambda/4$ , the band ratio can be increased.

Further, the embodiments of the present invention include the following concept.

Among the impedance layers constituting the acoustic mirror layer, at least one impedance layer may have a thickness of less than one fourth of an acoustic wavelength determined from a resonant frequency in free space of the piezoelectric thin film vibrator.

Thereby, at least one impedance layer has a thickness of less than one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator, and therefore, the resonance bandwidth can be broadened. By broadening the resonance bandwidth, a deterioration in resonance characteristics due to variations in the thickness of the impedance layer can be prevented.

When a plurality of low acoustic impedance layers and a plurality of high acoustic impedance layers, which are alternately

disposed, are provided, the uppermost low acoustic impedance layer may contact the lower electrode and have a thickness of less than one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator.

5 Thereby, the resonance bandwidth can be more effectively broadened.

The uppermost low acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 1.0%] or less. Thereby,  
10 the resonance bandwidth can be broadened without an influence of variations in the thickness.

The uppermost low acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the  
15 piezoelectric thin film vibrator minus 20.0%] or more. Thereby, the resonance bandwidth can be broadened without an influence of variations in the thickness.

Each low acoustic impedance layer may have a thickness of less than one fourth of the acoustic wavelength determined from  
20 the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be more effectively broadened.

Each low acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from  
25 the resonant frequency in free space of the piezoelectric thin

film vibrator minus 1.0%] or less. Thereby, the resonance bandwidth can be broadened without an influence of variations in the thickness.

Each low acoustic impedance layer may have a thickness of  
5 [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 20.0%] or more. Thereby, the resonance bandwidth can be broadened without an influence of variations in the thickness.

10 Each high acoustic impedance layer may have a thickness of less than one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be more effectively broadened.

15 Each high acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 1.0%] or less. Thereby, the resonance bandwidth can be broadened without an influence of variations in  
20 the thickness.

Each high acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 20.0%] or more. Thereby, the resonance  
25 bandwidth can be broadened without an influence of variations in

the thickness.

Each low acoustic impedance layer may have a thickness of less than one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator and each high acoustic impedance layer may have a thickness of less than one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator. Thereby, the resonance bandwidth can be more effectively broadened.

Each high acoustic impedance layer and each low acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 1.0%] or less. Thereby, the resonance bandwidth can be broadened without an influence of variations in the thickness.

Each high acoustic impedance layer and each low acoustic impedance layer may have a thickness of [the size of one fourth of the acoustic wavelength determined from the resonant frequency in free space of the piezoelectric thin film vibrator minus 20.0%] or more. Thereby, the resonance bandwidth can be broadened without an influence of variations in the thickness.

A ratio ( $Z_h/Z_l$ ) of an acoustic impedance ( $Z_h$ ) of each high acoustic impedance layer to an acoustic impedance ( $Z_l$ ) of each low acoustic impedance layer may be 4.82 or more. Thereby, the resonance bandwidth can be more effectively broadened.



Each high acoustic impedance layer may be made of silicon dioxide and each low acoustic impedance layer may be made of tungsten.

(Example of a filter comprising acoustic mirror type thin  
5 film bulk acoustic resonators)

FIGS. 24A and 24B are diagrams showing exemplary filters comprising acoustic mirror type thin film bulk acoustic resonators of the present invention. A one-pole filter 7 of FIG. 24A comprises acoustic mirror type thin film bulk acoustic resonators  
10 of any of the types of the first to fifth embodiments of the present invention, the resonators being connected in a L-shape. The first acoustic mirror type thin film bulk acoustic resonator 71 is connected to operate as a series resonator. Specifically, the first acoustic mirror type thin film bulk acoustic resonator 71  
15 is connected in series between an input terminal 73 and an output terminal 74. A second acoustic mirror type thin film bulk acoustic resonator 72 is connected to operate as a parallel resonator. Specifically, the second acoustic mirror type thin film bulk acoustic resonator 72 is connected between a path from the input  
20 terminal 73 to the output terminal 74, and a ground surface. Here, if a resonant frequency of the first acoustic mirror type thin film bulk acoustic resonator 71 is set to be higher than a resonant frequency of the second acoustic mirror type thin film bulk acoustic resonator 72, a ladder filter having a bandpass property can be  
25 obtained. Preferably, by setting the resonant frequency of the

first acoustic mirror type thin film bulk acoustic resonator 71 and an antiresonant frequency of the second acoustic mirror type thin film bulk acoustic resonator 72 to be substantially equal or close to each other, a ladder filter having a flatter passband  
5 can be obtained.

Although an L-shaped structure ladder filter is described in the above example, the same effect can be obtained in other ladder filters having a T-shaped structure, a  $\pi$ -shaped structure, a lattice structure and the like. The ladder filter may have one  
10 pole as in FIG. 24A or a plurality of poles as in FIG. 24B or the like. If at least one of the thin film bulk acoustic resonators has the feature of any of the first to ~~fifith~~fifth embodiments, a filter having a broadband effect can be obtained.

(First example of an apparatus comprising acoustic mirror  
15 type thin film bulk acoustic resonators)

FIG. 25 is a diagram showing a first exemplary apparatus comprising an acoustic mirror type thin film bulk acoustic resonator of the present invention. The apparatus 9a of FIG. 25 is a duplexer comprising the filter of FIG. 24B. The apparatus 9a  
20 comprises a Tx filter (transmission filter) 91 including a plurality of acoustic mirror type thin film bulk acoustic resonators, an Rx filter (reception filter) 92 including a plurality of acoustic mirror type thin film bulk acoustic resonators, and a phase-shift circuit 93 including two  
25 transmission lines. The Tx filter 91 and the Rx filter 92 are

filters which have optimum frequency arrangement, thereby making it possible to obtain a duplexer having excellent properties, such as low loss and the like. Note that the number of filters, the number of acoustic mirror type thin film bulk acoustic resonators included in the filter, and the like can be freely designed, but not are limited to that shown in FIG. 25. Note that at least one of the Tx filter 91 and the Rx filter 92 is a filter which comprises two or more thin film bulk acoustic resonators connected in a ladder form and in which at least one of the thin film bulk acoustic resonators has the feature of any of the first to fifth embodiments.

(Second example of an apparatus comprising acoustic mirror type thin film bulk acoustic resonators)

FIG. 26 is a diagram showing a second exemplary apparatus comprising an acoustic mirror type thin film bulk acoustic resonator of the present invention. The apparatus 9b of FIG. 26 is a communication apparatus comprising the duplexer of FIG. 25. The apparatus 9b comprises an antenna 101, a divider 102 for separating two frequency signals, and two duplexers 103 and 104. Either the duplexer 103 or the duplexer 104 is the duplexer of FIG. 25. Thus, by using a duplexer having an excellent property, such as low loss or the like, a low-loss communication apparatus can be achieved.

(Third example of an apparatus comprising acoustic mirror type thin film bulk acoustic resonators)

FIG. 27 is a diagram showing a third exemplary apparatus

comprising an acoustic resonator of the present invention. The apparatus 9c of FIG. 27 is a communication apparatus comprising the filter of FIG. 24A or 24B. The apparatus 9c comprises two antennas 111 and 112, a switch 113 for switching two frequency signals, and two filters 114 and 115. The communication apparatus of FIG. 27 is different from the communication apparatus of FIG. 26 in that the switch 113 is used instead of the divider 102, and the filters 114 and 115 are used instead of the duplexers 103 and 104. Also with this structure, a low-loss communication apparatus can be obtained. The communication apparatus of the present invention is not limited to those of FIGS. 26 and 27 and may be any communication apparatus comprising at least one bulk acoustic resonator of the present invention.

While the invention has been described in detail, the foregoing description is in all aspects illustrative and not restrictive. It is understood that numerous other modifications and variations can be devised without departing from the scope of the invention.

## INDUSTRIAL APPLICABILITY

The acoustic mirror type thin film bulk acoustic resonator of the present invention, and a filter, a duplexer and a communication apparatus each comprising the same, can have a broad resonance bandwidth, thereby preventing a deterioration in resonance characteristics due to variations in thickness of an

acoustic mirror layer and being useful for a wireless apparatus and the like.

# ABSTRACT

A thin film bulk acoustic resonator ~~(507b)~~ comprises including (i) a substrate ~~(101b)~~, (ii) an acoustic mirror layer ~~(508b)~~ provided disposed on the substrate ~~(101b)~~, and including a plurality of impedance layers ~~(502b, 503b)~~ alternately having a high acoustic impedance and a low acoustic impedance, and (iii) a piezoelectric thin film vibrator ~~(509b)~~ provided disposed on the acoustic mirror layer ~~(508b)~~, including a lower electrode ~~(504b)~~, a piezoelectric thin film ~~(105b)~~ and an upper electrode ~~(506b)~~. The sum of a thickness of the lower electrode ~~(504b)~~ and a thickness of the upper electrode ~~(506b)~~ is between 5% or more and 60% or less of a whole thickness of the piezoelectric thin film vibrator ~~(509b)~~, and the thickness of the lower electrode ~~(504b)~~ is larger than the thickness of the upper electrode ~~(506b)~~.